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AN EXAMINATION OF SOME NEW AND CLASSICAL SHORT PERIOD DISCRIMINANTS

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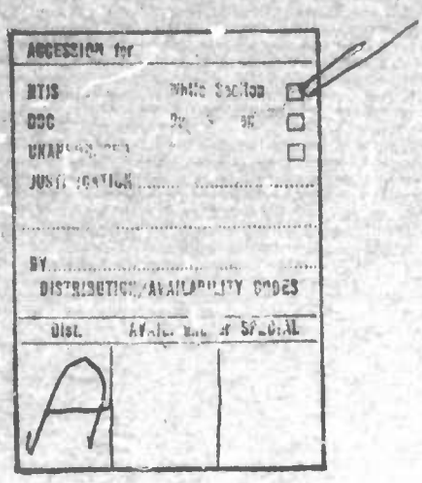
It is shown that for the spectral ratio discriminant the discriminatory power lies in the ratio .4-.8 Hz energy to 1.0 Hz energy, and that the higher frequency energy has no additional discriminatory power. We find that the explosions which fail to discriminate were probably cratering experiments. In either this case, or if the explosion is deep, pP will not cancel P at low frequencies. Thus, we propose that pP-P cancellation is the basic physical explanation for the success of short period discrimination.



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AN EXAMINATION OF SOME NEW AND CLASSICAL
SHORT PERIOD DISCRIMINANTS

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It is shown that for the spectral ratio discriminant the discriminatory power lies in the ratio of .4-.8 Hz energy to 1.0 Hz energy, and that the higher frequency energy has no additional discriminatory power. We find that the explosions which fail to discriminate were probably cratering experiments. In either this case, or if the explosion is deep, pP will not cancel P at low frequencies. Thus, we propose that pP-P cancellation is the basic physical explanation for the success of short period discrimination.

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INTRODUCTION

The use of short period data in discriminating between seismic records originating from earthquakes and explosions can be important, especially when a reliable estimate of the surface wave magnitude cannot be obtained from the corresponding long period records. In the case where both long-period surface wave and short-period body wave magnitudes are measured, one can achieve fairly good discriminability on the basis of these two measurements alone (see, for example, Lacoss, 1969; Capon et al., 1969; Shumway and Blandford, 1970; Shumway and Blandford, 1972). However, it is reasonable to suppose that the short-period waveforms contain more discrimination information than can be inferred solely from the magnitude of the body wave. This speculation is coupled with the fact that the body wave magnitude is useless without the corresponding surface wave magnitude which may not be observable. The above objections justify a more detailed investigation of the discriminatory capabilities of the short-period waveforms.

The two most prominently mentioned spectral discriminants are termed the spectral ratio and complexity. The spectral ratio operates on the hypothesis that the ratio of low frequency energy to high frequency energy for the source spectrum of earthquakes exceeds that for explosions. (See, for example, Booker and Mitronovas, 1964.) Blandford, 1974, however, has developed a theory suggesting that this hypothesis does not always hold. In a technical report Kelly, 1968, and two reports of Lacoss, 1969, showed that the spectral ratio could produce a reasonable separation when applied to suites of earthquakes and explosions. A second discriminant is suggested if one assumes that explosions are basically impulsive while earthquakes generally have a more complicated waveform. A measure of complexity consisting of the total energy in the signal coda has been applied in Carpenter, 1964, and Kelly, 1968, with some success.

An appreciation for the possible discriminatory capabilities of the two discriminants may be gained by inspecting Figure 1 which summarizes the data from the 40 presumed earthquakes and 26 presumed explosions given in Figures A1 and A2 in Appendix I. The traces are LASA beams for events located between 40 and 60°N latitude and between 70 and 90°E longitude plus other selected "difficult" events (see Appendix I). The original data traces were gain adjusted to a unit amplitude, aligned on first motion and averaged to produce the earthquake and explosion signals shown in the left half of Figure 1. We see that the earthquake signal tends to have more energy in the coda suggesting that complexity might be a useful discriminant. The average earthquake and explosion noise spectra were computed by subtracting from each trace its mean signal (the mean explosion or mean earthquake) and then computing the average spectrum of the residuals. These "error spectra" tend to display greater power at low frequencies for the earthquakes indicating that a spectral ratio could be used as a discriminant. Averages from a randomly drawn subset of the population, shown on the right half of Figure 1, suggests that the observations made above hold fairly consistently for both earthquakes and explosions.

The earthquake and explosion signals in Figure 1 also suggest that more information may be available than would be provided by the previously discussed spectral and complexity measures. For example, the rather regular pattern in the mean earthquake coda is essentially the averaging of the later phases which can be observed on the original earthquake traces in Figures A1 and A2. The consistency displayed by the mean codas of the full and subset populations indicates that the pattern might be a general characteristic of earthquakes from this region. On the other hand, they may be effects associated with the geographical source regions, and an explosion set off at the earthquake site might show the same phasing. Arguing heuristically from Figure 1, there are reasons for believing that earthquakes and explosions are composed of (a) fixed mean waveforms which are different and

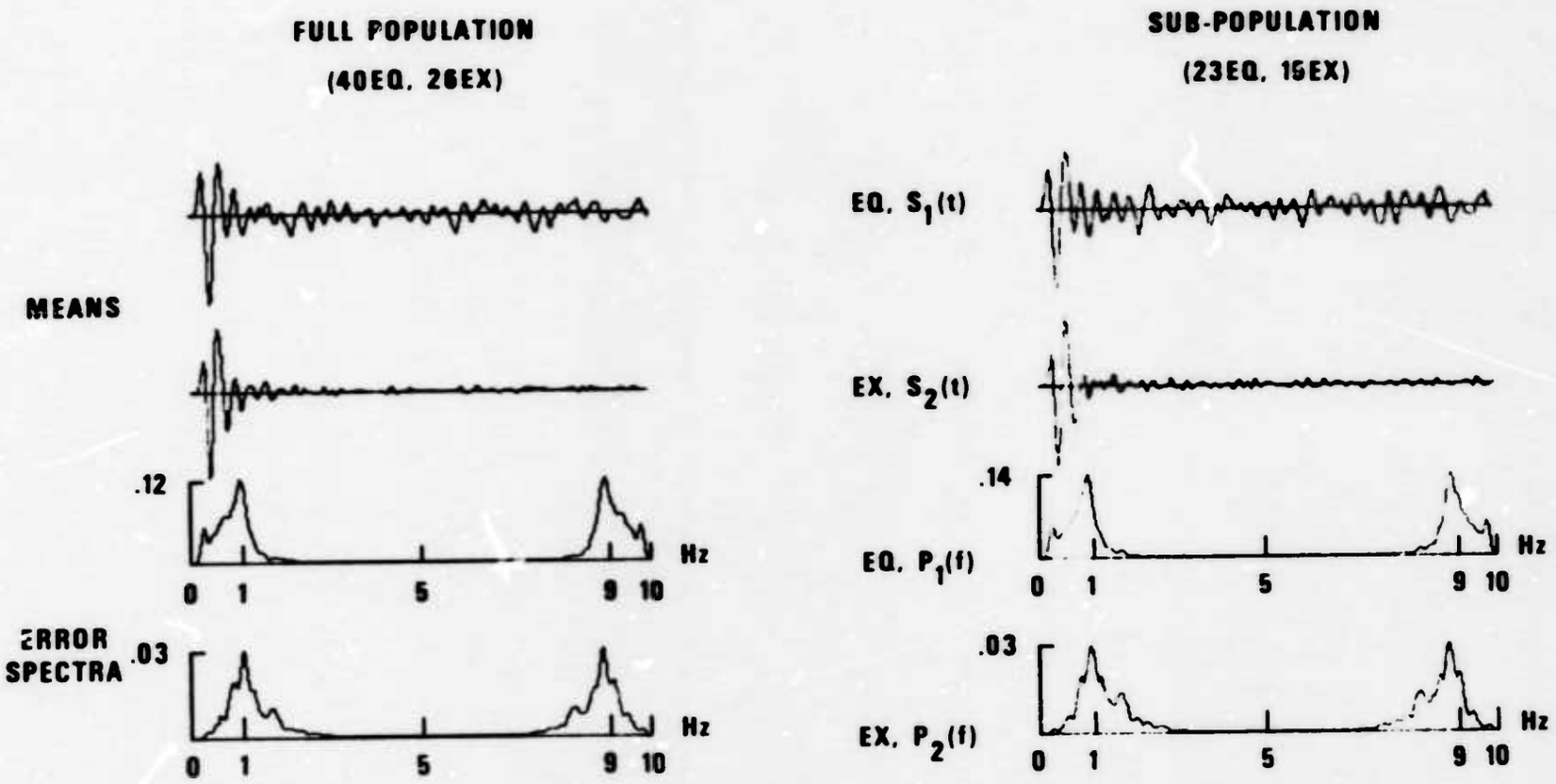

Figure 1. Mean Signals and Noise Spectra for the Full Population and a Sub-Population Used as a Learning Set.

(b) stochastically varying noises with different spectra. If the residual noise processes are Gaussian and stationary, the problem may be formulated in classical discrimination detection terms. That is, denoting the received waveform, signal and noise (not earth noise) respectively by x, s and n, we have the two hypotheses H_1 (Earthquake) and H_2 (Explosion) specifying

$$\begin{aligned} H_1: \quad & x = s_1 + n \\ H_2: \quad & x = s_2 + n \end{aligned} \tag{1.1}$$

where n has zero means and autocorrelation matrices R_1 and R_2 respectively under H_1 and H_2. In this case the optimum detector is the sum of the outputs of a quadratic filter and a linear filter, where optimality is defined as maximizing the explosion detection probability for a fixed false alarm rate (see Anderson, 1958). Because of the distributional problems associated with the output of this quadratic detection filter (QDF), it is useful to consider several versions of an optimum linear filter. We shall consider the linear detection filter (LDF) which gives the highest detection probability of any linear filter and the linear matched filter (LMF) which is optimum if n is a white noise process with equal power under both H_1 and H_2. Matched filters have been applied to detecting long period signals by Glover and Alexander, 1968, and Alexander and Lambert, 1971, who used a seismic signal as the reference event. Capon et al., 1969, produced comparable results using a chirp waveform instead of a seismic signal.

In this report we will consider the application of the classical spectral measures and optimum linear and quadratic filtering to the population of earthquakes and explosions shown in Figures A1 and A2 of the Appendix. For referral purposes the discriminants considered are listed below:

(1) Linear Detection Filter (LDF)

(2) Linear Matched Filter (LMF)

(3) Quadratic Detection Filter (QDF)

(4) Integrated Spectra (.4-.8 Hz)

(4)' Integrated Spectra (1.4-1.8 Hz)

(5) Complexity

(6) Complexity vs Integrated Spectra (.4-.8 Hz)

The distribution theory for discriminants (1), (2), (4) and (4)' will be given which allows the explosion false alarm and detection probabilities to be explicitly calculated. The procedure for using the above discriminants will be tested by using a random subset of the total to derive the relevant parameters and then testing the derived discriminants on the remaining events. Sections 2, 3 and 4 give the equations for the various proposed discriminants and summarize the results of applying the discriminants to the full suite of events. Section 5 presents the results of using discriminants derived from a randomly drawn learning set to discriminate on the remaining presumed "new" events. In Section 6 we discuss the physical basis for the discriminants as a guide to the expected behavior on new events, and give suggestions for further research.

LINEAR FILTERING

In this section we will investigate linear filtering as a technique for discriminating between hypotheses H_1 and H_2 as specified in equation (1.1). To be more precise, assume that under the hypothesis H_j, $j = 1, 2$, the T dimensional observed vector $x' = [x(0), x(1),..., x(T-1)]$ is a non-stationary normal process with mean signal vector $s_j' = [s_j(0),..., s_j(T-1)]$ and covariance matrix

$$E_j(x-s_j)(x-s_j)' = R_j. \tag{2.1}$$

Since the noise is stationary R_j is assumed to contain covariance functions of the form

$$R_j(k-\ell) = \int_{-1/2}^{1/2} e^{2\pi i(k-\ell)f} P_j(f)\,df \tag{2.2}$$

in the k^{th} row and ℓ^{th} column. Hence, an equivalent statement of the hypothesis H_j is that x is a normal process with mean s_j and noise power spectrum $P_j(f)$. Define the difference between the earthquake and explosion vectors as

$$\delta = s_1 - s_2. \tag{2.3}$$

We seek a linear filter, say b'x, to use for classifying x into H_1 or H_2. An observation is classified into H_1 if $b'x > c$ and into H_2 if $b'x \leq c$. A simple possibility is matching the mean difference vector δ with the data vector x producing the matched filter output $\delta'x$. If $R_1 = R_2 = \sigma^2 I_T$ with I_T the T x T identity matrix, the probability of detecting H_2 for a fixed false alarm rate will be maximized. If $R_1 = R_2 = R$, i.e. $P_1(f) = P_2(f) = P(f)$, the classical linear discriminant function $\delta'R^{-1}x$ maximizes the detection probability as shown in Anderson, 1958.

If $R_1 \neq R_2$, Kullback, 1959, has shown that for a fixed false alarm rate α, a discriminant filter of the form

$$y(t_1,t_2) = \delta' \bar{R}^{-1} x \tag{2.4}$$

maximizes the detection probability where

$$\bar{R} = t_1 R_1 + t_2 R_2 \tag{2.5}$$

is a weighted combination of the auto-correlation matrices and t_1 and t_2 are chosen (subject to the condition that $\bar{R}$ be positive definite) to maximize the detection probability.

$$P_d(\alpha) = P_{H_2}\{\text{accept } H_2\} = \Phi\left(\frac{d + \Phi^{-1}(\alpha)\sigma_1}{\sigma_2} \right) \tag{2.6}$$

with

$$\sigma_j^2 = \delta' \bar{R}^{-1} R_j \bar{R}^{-1} \delta \tag{2.7}$$

$$d = \delta' \bar{R}^{-1} \delta \tag{2.8}$$

and

$$\Phi(x) = \int_{-\infty}^{x} e^{-u^2/2} \frac{du}{\sqrt{2\pi}}. \tag{2.9}$$

We have chosen to maximize the probability of detecting an explosion for a given false alarm rate. A parallel investigation of the filters which maximized the earthquake detection probability for a given explosion false alarm rate gave approximately the same filters and performance results. Anderson and Bahadur, 1962, discuss the admissibility of estimators having this same general form. The general procedure for using equations (2.5)-(2.9) is first to choose an α and then to search over t_1 and t_2 for the maximum $P_d(\alpha)$ as defined in equation (2.6).

The difficulty in applying equation (2.6) arises from the computational effort involved in the matrix calculations (2.7) and (2.8). If T x T (in this case T = 256) matrices are involved, even the Levinson recursion would lead to excessive

computer time because of the number of repetitions necessary to maximize (2.6). However, a spectral approximation method based on the finite Fourier transform (FFT) can be employed which yields a great saving in computer time. Spectral approximations were proposed for a problem involving only spectra by Capon, 1965, and we refer to Shumway and Unger, 1974, for the conditions under which the following approximations are valid. The important condition is that all spectra involved in the equations be strictly positive.

Suppose that the FFT of the function $g(t)$, $t = 0, 1, \ldots, T-1$ is defined as usual by

$$G(\lambda_n) = T^{-1/2} \sum_{n=0}^{T-1} g(t) e^{-i\lambda_n t} \tag{2.10}$$

where

$$\lambda_n = 2\pi f_n, \quad f_n = \frac{n}{T} \tag{2.11}$$

with f_n corresponding to f in equation (2.2) and λ_n denoting the angular frequency. Then, approximations to (2.7) and (2.8) are

$$\sigma_j^{o2} = \sum_{n=0}^{T-1} |D(\lambda_n)|^2 \frac{P_j(\lambda_n)}{\bar{P}(\lambda_n)} \tag{2.12}$$

and

$$d^o = \sum_{n=0}^{T-1} \frac{|D(\lambda_n)|^2}{\bar{P}(\lambda_n)} \tag{2.13}$$

where $D(\lambda_n)$ is the FFT of $\delta(t)$, $P_j(\lambda_n)$ is the spectrum of x under H_j and

$$\bar{P}(\lambda_n) = t_1 P_1(\lambda_n) + t_2 P_2(\lambda_n). \tag{2.14}$$

Shumway and Unger, 1974, show that $T^{-1}\sigma_j^2$ and $T^{-1}\sigma_j^{o2}$ have the same finite limit and that $T^{-1}d$ and $T^{-1}d_o$ have the same finite limit. The linear detection filter (2.4) (LDF) may then be approximated by

$$y^o(t_1,t_2) = \sum_{n=0}^{T-1} \frac{D^*(\lambda_n)X(\lambda_n)}{\bar{P}(\lambda_n)} \tag{2.15}$$

where $X(\lambda_n)$ is the FFT of the data trace $x(t)$ and * denotes the complex conjugate.

We refer to (2.15) from here on as the linear detection filter (LDF).

The linear matched filter (LMF) is given by

$$Z = \delta' x = \sum_{n=0}^{T-1} D^*(\lambda_n)X(\lambda_n) \tag{2.16}$$

and has detection probability approximated by

$$P_d'(\alpha) = \Phi \frac{d' + \Phi^{-1}(\alpha)\sigma_1^{o'}}{\sigma_2^{o'}} \tag{2.17}$$

with

$$(\sigma_j')^2 = \sum_{n=0}^{T-1} |D(\lambda_n)|^2 P_j(\lambda_n) \tag{2.18}$$

and

$$d' = \sum_{n=0}^{T-1} |D(\lambda_n)|^2. \tag{2.19}$$

In order to apply the LDF and LMF to the full suite of 40 earthquakes and 26 explosions given in the Appendix, estimates for $s_1(t)$, $s_2(t)$, $P_1(\lambda_n)$ and $P_2(\lambda_n)$ are needed. If we regard $x_{jk}(t)$ as the k^{th} observed event of type j, j=1,2, k=1,...,N_j, we may estimate the j^{th} signal process by

$$\hat{s}_j(t) = N_j^{-1} \sum_{k=1}^{N_j} x_{jk}(t) \tag{2.20}$$

and the j^{th} noise spectrum by

$$\hat{P}_j(\lambda_n) = (N_j-1)^{-1} \sum_{k=1}^{N_j} |X_{jk}(\lambda_n) - \hat{S}_j(\lambda_n)|^2 \tag{2.21}$$

where the capital letters denote, as usual, the FFT. These estimators (after smoothing with a three point running average) are shown on the left side of Figure 1. In this example T = 256 points are sampled at 10 points per second yielding a folding frequency of 5 Hz.

A search over the possible values for t_1 and t_2 yielded $t_1 = t_2 = 1$ as the solution which maximized the detection probability for a false alarm rate for explosions of $\alpha = .001$. The predicted explosion detection probability for this false alarm rate is .997 with a threshold for the detector established as $C = -8.51$, i.e. we accept H_1 (earthquake) if $y^o(1,1) > -8.51$ or H_2 (explosion) if $y^o(1,1) \leq -8.51$. The filter for this case is

$$y^o(1,1) = \sum_{n=0}^{T-1} \frac{D^*(\lambda_n)X(\lambda_n)}{P_1(\lambda_n)+P_2(\lambda_n)}$$

so that we may look at it as a matching of the signal difference vector $D(\lambda_n)$ with the data $X(\lambda_n)$ where the weights are inversely proportional to the average spectrum. The vertical axis in Figure 2 shows the output of the LDF and it is clear that 38 of 40 earthquakes and 22 of 26 explosions would be detected for a .001 explosion false alarm rate. Adjusting the threshold slightly picks up one more explosion. The predicted detection probability for explosions is .997. Several difficult events are causing some problems. The main defect appears to be the assumption that each earthquake has the same noise spectrum and that each explosion has the same noise spectrum even though the spectra for earthquakes and explosions may differ. In the discussion we trace this fact to the possibility that some of the explosions are cratering experiments, and that some of the earthquakes are on P-wave radiation nulls which are more effective at long periods than at short periods. The missed events are marked in the Appendix with a (1) and (2) depending on whether the LDF or LMF failed to detect. For an explosion false

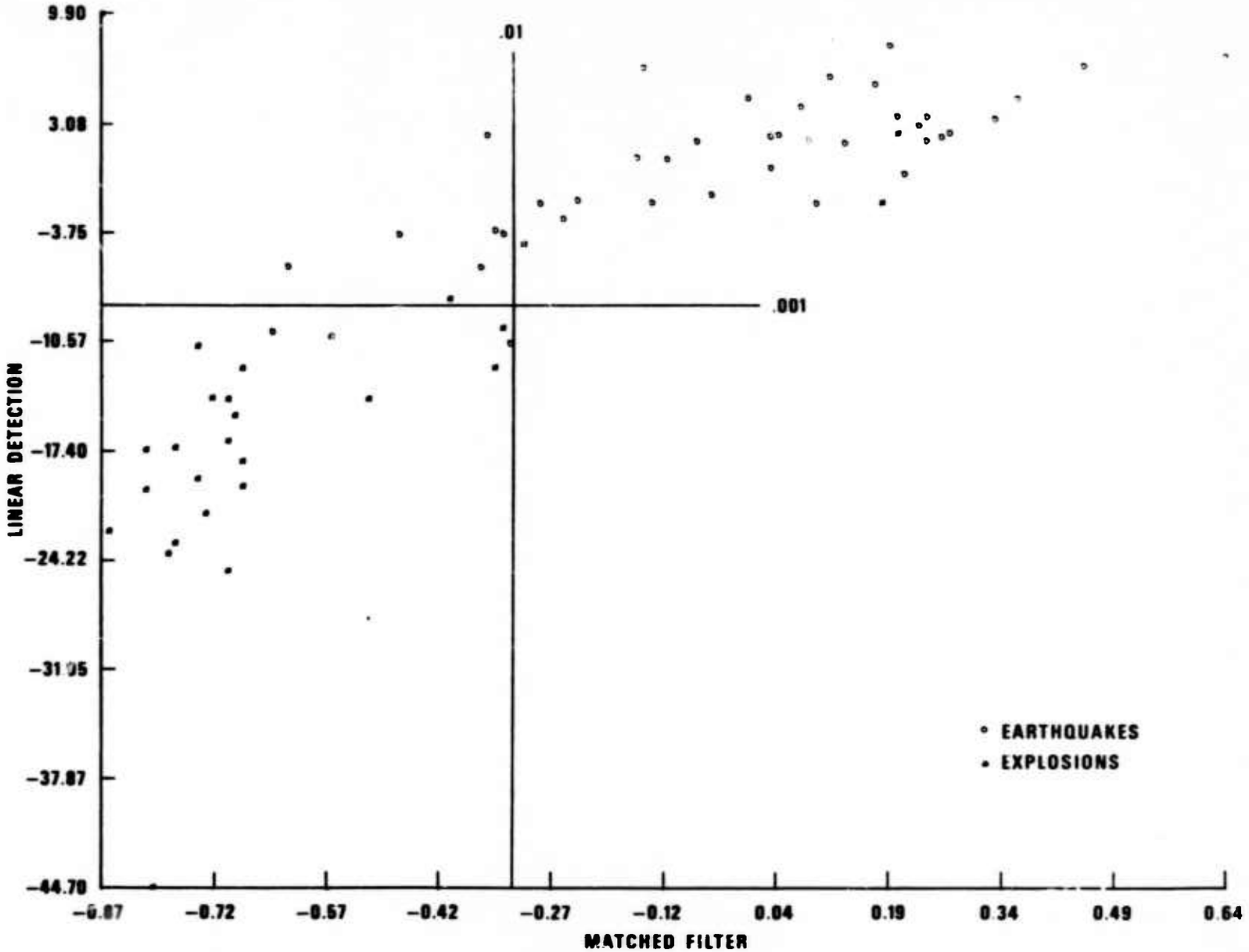

Figure 2. Output of Linear Detection Filter (LDF) and Linear Matched Filter (LMF) Applied to Full Suite of Events.

TABLE I

Estimated Filter Parameters for the Full Population and Sub-Population*

Filter Characteristics	Full		Sub	
	LDF	LMF	LDF	LMF
Mean (H_1)	1.0	.01	3.4	.09
Mean (H_2)	-15.9	-.59	-13.5	-.53
Var (H_1)	9.5	.041	9.8	.042
Var (H_2)	7.4	.012	7.0	.011
Threshold	- 8.51	-.32	- 6.27	-.39
(t_1,t_2)	(1,1)		(1,1)	

*The sub-population or learning set contained earthquakes (1, 4, 6, 8, 10, 11, 13, 14, 15, 16, 21, 24, 25, 26, 27, 28, 30, 31, 32, 35, 36, 37, 40) and explosions (2, 3, 6, 7, 8, 9, 11, 15, 17, 18, 21, 23, 24, 25, 26).

alarm probability of .01 and detection probability .99, the linear matched filter (LMF) shown as the horizontal axis in Figure 2 detected 23 of 26 explosions but only 32 of 40 earthquakes. The filter means and variances are shown in Table I. We note here that the proper method for evaluating the detectors is to randomly choose a subset of events to estimate the filter parameters and then apply the filters derived to the remaining events. This procedure will be followed in the Experimental Results section.

OPTIMUM QUADRATIC FILTERING

While the LDF of the previous section is the optimum linear filter, it is not the optimum filter in general when the spectra of the earthquakes and explosions are different. In this case, the likelihood approach yields a quadratic form for determining whether an observation x comes from H_1 or H_2 (see Anderson, 1958). In this case the log likelihood ratio

$$S(x) = -\frac{1}{2}(x-s_1)'R_1^{-1}(x-s_1) + \frac{1}{2}(x-s_2)'R_2^{-1}(x-s_2) \qquad (3.1)$$

classifies by comparing the weighted distance between x and s_1 with the weighted distance between x and s_2. A spectral approximation to S(x) is given by

$$S^o(x) = -\frac{1}{2}\sum_{n=0}^{T-1}\frac{|X(\lambda_n)-S_1(\lambda_n)|^2}{P_1(\lambda_n)} + \frac{1}{2}\sum_{n=0}^{T-1}\frac{|X(\lambda_n)-S_2(\lambda_n)|^2}{P_2(\lambda_n)} \qquad (3.2)$$

where the FFT's and power spectra are as given in Section 2 and the difference $T^{-1}|S(x)-S^o(x)|$ converges (with probability 1) to zero.

One difficulty with applying S(x) or $S^o(x)$ as a discriminant is that the probability distributions used for computing detection probabilities are not tractable. However, it is known that the theoretical detection probability of the quadratic detection filter will exceed that of any LDF. The only real problem are setting the proper threshold and worrying about the effects of the estimated spectra and signal means on the value of (3.2).

Figure 3 shows the result of applying the discriminant (3.2) to the full suite of events. We see that a threshold set at about .10 would have detected 38 out of 40 earthquakes and 24 out of 26 explosions. The misclassifications are marked on the

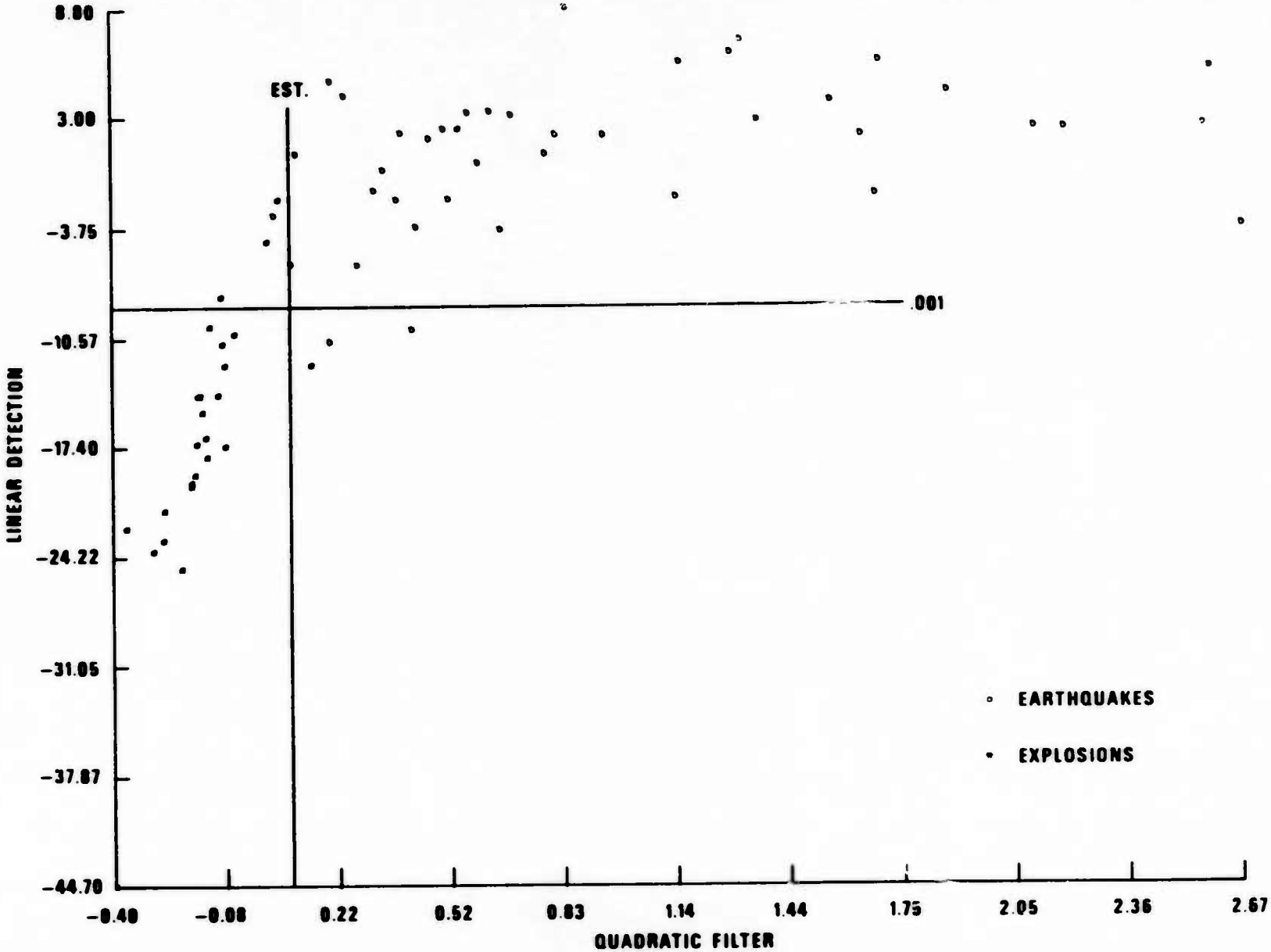

Figure 3. Output of Quadratic Detection Filter (QDF) and Linear Detection Filter (LDF) Designed and Applied to Full Suite of Events. Quadratic threshold at 0.1 estimated visually.

the original traces in Figures A1 and A2 with a (3). Again, while the qualitative characteristics of the QDF appear to be excellent, we defer making any comparative statements before the Experimental Results section.

SPECTRAL RATIOS AND COMPLEXITY

The basic measure of interest here is the integrated spectrum as measured by the periodogram accumulated over some frequency band of interest. In spectral ratio computations, it is customary to use a low frequency band as the range .4-.8 Hz and a high frequency band as the range 1.4-1.8 Hz.

The integrated spectral estimate centered at f_o Hz or at radial frequency $\lambda_o = 2\pi f_o$ with f_o a multiple of 1/T was defined as ($L < (1/2)T$)

$$\hat{LP}(\lambda_o) = \sum_{s=-1/2(L-1)}^{1/2(L-1)} |X(\lambda_o + \tfrac{2\pi s}{T})|^2 \qquad (4.1)$$

where X(.) denotes the FFT of the time series x(.). If the spectrum is relatively smooth over the band of interest then, approximately, under H_j

$$\hat{LP}(\lambda_o) \sim \frac{\chi^2_{2L}}{2L} \left(LP_j(\lambda_o) \right) , \qquad (4.2)$$

where ~ denotes "is distributed as" and χ^2_{2L} denotes a chi-square variable with 2L degrees of freedom. Note that the spectrum $P_j(\lambda_o)$ is regarded here as containing both a stochastic signal and a stochastic noise process. Equation (4.2) allows one to set a threshold for the sample cumulative spectrum $\hat{LP}(\lambda_o)$ if we know the earthquake spectrum $P_1(\lambda_o)$ and the explosion spectrum $P_2(\lambda_o)$. For the example suppose that $P_1(\lambda_o) > P_2(\lambda_o)$ and we accept H_1(earthquake) if $\hat{LP}(\lambda_o) > C$ and we accept H_2(explosion) if $\hat{LP}(\lambda_o) \leq C$. Then, the explosion false alarm rate is

$$\alpha = P_{H_1} \left\{ \hat{LP}(\lambda_o) \leq C(\alpha) \right\} = P \left\{ \frac{\chi^2_{2L}}{2L} \leq \frac{C(\alpha)}{LP_1(\lambda_o)} \right\} . \qquad (4.3)$$

Solving the above equation for $C(\alpha)$ determines the threshold, with the detection probability given by (4.3). If there are spectral estimates in another non-overlapping frequency band

centered at λ_1, the classical "spectral ratio" will have an F distribution.

Figure 4 shows the cumulative spectra for two band, .4-.8 Hz (f_o = .6 Hz) and 1.4-1.8 Hz (f_o = 1.6 Hz). Since the traces are normalized to a unit amplitude which tends to have a period near one-second, the low and high frequency spectra tend to measure the energy content relative to 1 Hz. From the plots we observe that the low frequency integrated spectrum discriminates completely. As we shall see in the Discussion section, this is probably due to the cancellation of P by pP at low frequencies for explosions. The threshold values are derived by noting that in this case L = 11 in (4.2) with $X^2_{22}(.01)/22$ and $X^2_{22}(.99)/22$ given by .434 and 1.83 respectively. In order to arrive at reasonable values for $LP_1(\lambda_o)$ and $LP_2(\lambda_o)$, the integrated spectra were averaged for earthquakes and explosions to give $P_1(\lambda_o)$ = .5802 and $P_2(\lambda_o)$ = .1372 for the band .4-.8 Hz. A cutoff point, set at C(.01) = .22 yields a predicted detection of Pd(.01) = .99. In this case the sample results are that 24 out of 26 explosions and 32 out of 40 earthquakes are detected. Adjusting the threshold detects 3 additional earthquakes. The high frequency band (1.4-1.8 Hz) performs poorly and these values were ignored. The incorrect classifications for the spectral discriminator are indicated by the code (4) in Figures A1 and A2.

Complexity is measured by some function proportional to the total integrated power in the signal coda. Here, the coda is defined as the part of the signal beginning after the 60th point (6 seconds). Figure 5 shows complexity plotted against the integrated low frequency spectrum and we note that with a graphically determined cutoff at .25 we detect 22 of 26 explosions and 36 out of 40 earthquakes. The combining of complexity and integrated low frequency spectral measurements tends to improve the

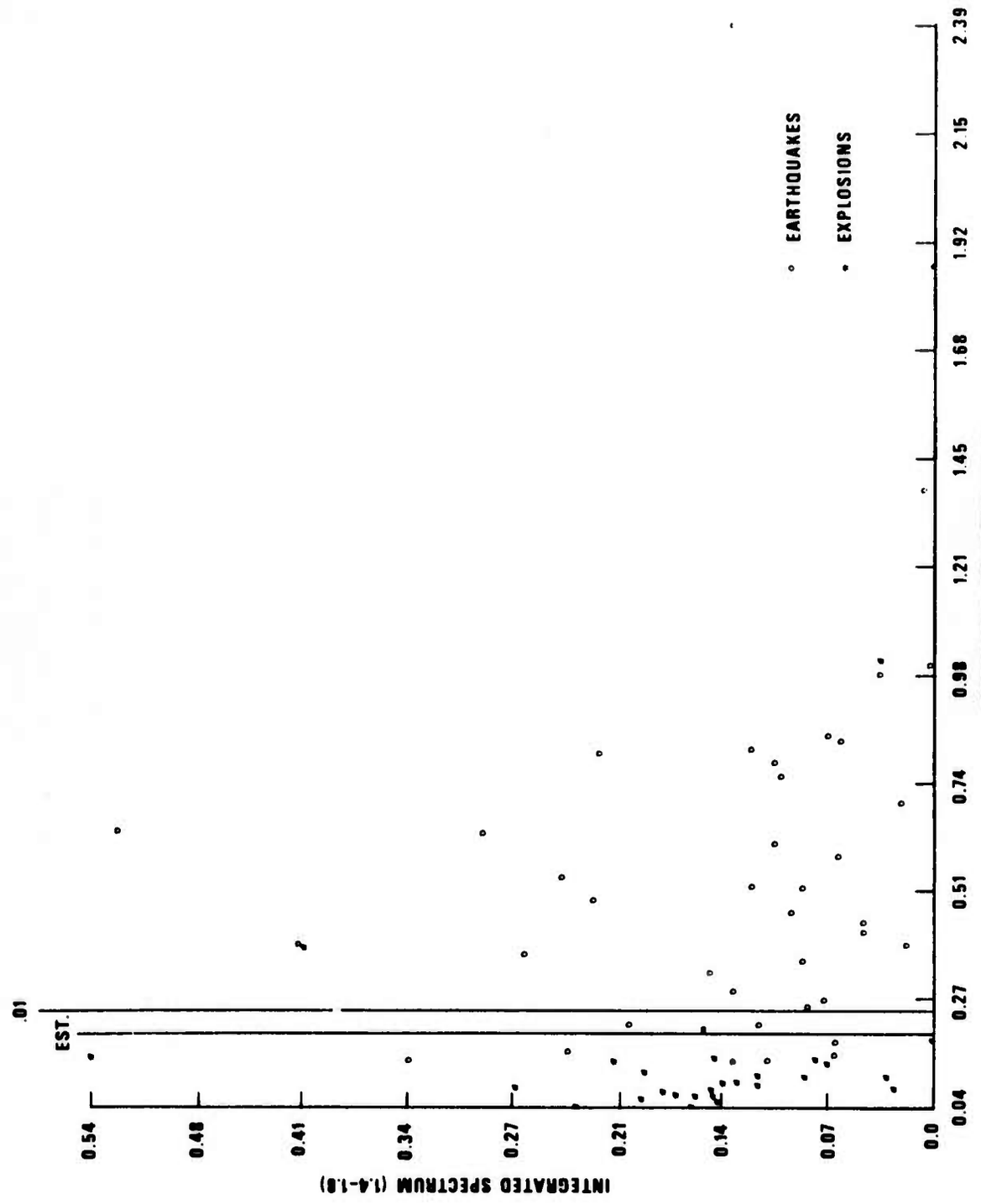

Figure 4. Components of Spectral Ratio for Full Suite of Events.

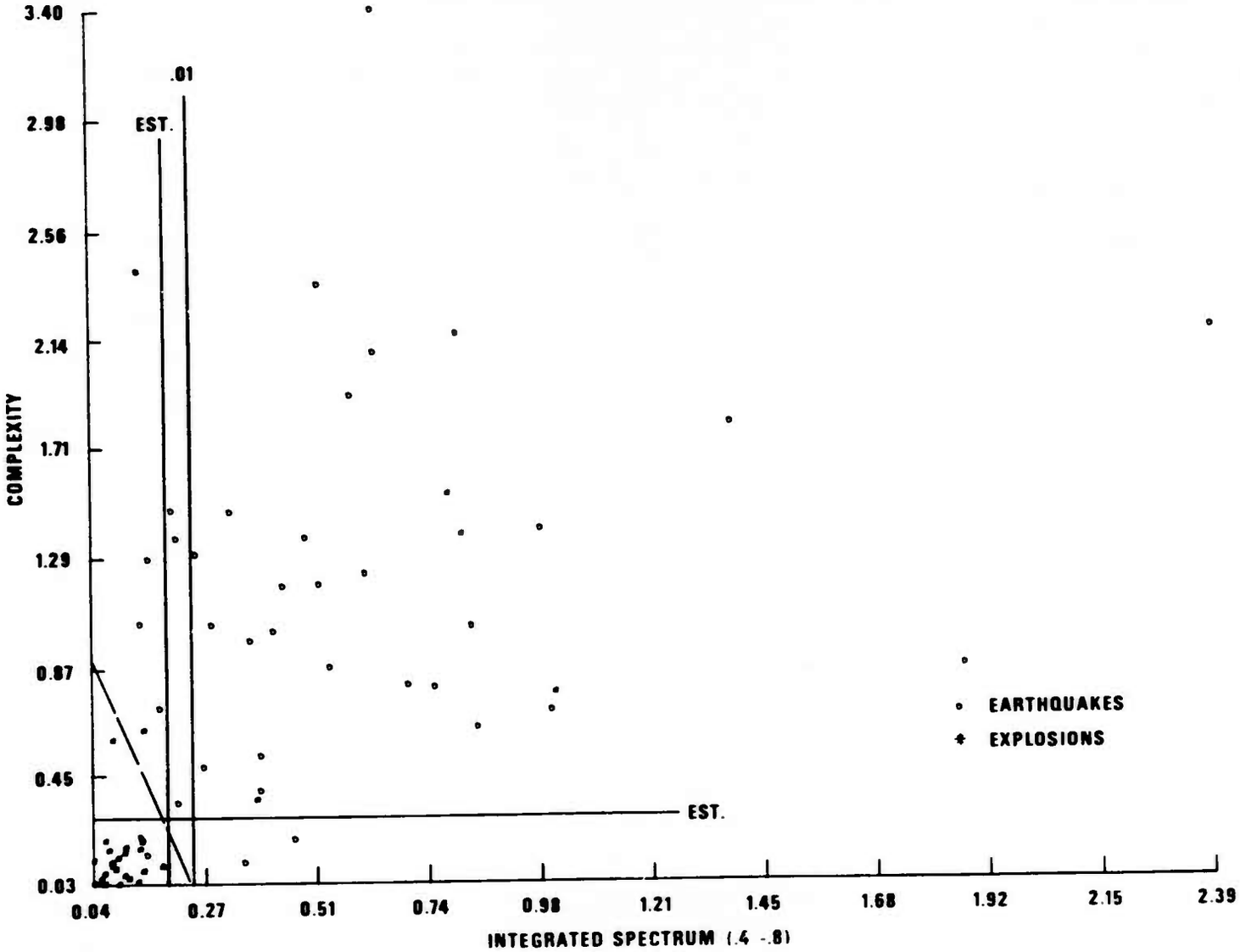

Figure 5. Complexity and Low Frequency Component of Spectral Ratio for Full Suite of Events.

overall discrimination if one is willing to draw a negatively sloped separation line. Such a line can (see Figure 5) be adjusted to detect 23 of 26 explosions and 38 of 40 earthquakes. A negatively sloped line has been obtained by Anglin, 1971. Blandford, 1974, has also discussed the simultaneous increase in complexity and decrease in low frequency power for earthquakes from a theoretical point of view.

It is worth noting that the relative ineffectiveness of the 1.4-1.8 Hz band energy can be deduced by inspection of Figures 13 and 14 in LaCoss (1969-24). These figures plot 0.4-0.8 Hz and 1.4-1.8 Hz energy versus m_b, and one sees a far greater separation for the low frequency band.

EXPERIMENTAL RESULTS

All of the discriminants involved here need some prior data in order to establish a decision criterion for future observations. The filtering discriminants, LDF, LMF, QDF all need a reference earthquake and a reference explosion to match against a new event of unknown origin. In addition, the LDF and QDF need prior estimates of the earthquake and explosion spectra in order to determine the proper weighting functions in the filter and to establish a threshold value for the discriminant when it is applied to a new data trace. The "spectral ratio" (normalized integrated spectrum, .4-.8 Hz) and complexity also require an initial learning set to determine a threshold value for new data.

In order to test the discriminants under realistic conditions, a sub-population of 23 earthquakes and 15 explosions was drawn randomly from the full suite of 40 earthquakes and 26 explosions. The mean signals and spectra for the subset are shown on the right hand half of Figure 1. It is clear that the waveforms and spectra determined for the random sample do not differ greatly from those determined from the full suite of events. Table I compares the means, variances and threshold values for the linear detection and linear matched filters. All characteristics noticeable in the full set seemed to be present in the learning set.

The parameters given by the learning set were then used to derive the discriminants to be applied to the events not in the learning set, now presumed to be new events of unknown origin. Table II summarizes the results of applying the discriminants derived from the learning set to both the learning population and the population of new observations. The cutoff values determined from the sub-population for the quadratic detector spectral ratio and complexity were .10, .22 and .25 respectively. Several qualitative observations can be made about the various detectors. The quadratic filter had a perfect record on the learning set

TABLE II

Summary of Experiment Using the
Linear Detection Filter (LDF), Linear Matched Filter (LMF),
Quadratic Detection Filter (QDF), Spectral Ratio (SR),
Complexity (C), and Complexity vs Spectral Ratio (CSR)

Learning Set

	Total	Number Detected					
		LDF	LMF	QDF	SR	C	CSR
Number of Earthquakes	23	22	23	23	20	21	23
Number of Explosions	15	14	11	15	14	12	13

Test Set

	Total	Number Detected					
		LDF	LMF	QDF	SR	C	CSR
Number of Earthquakes	17	17	15	15	13	15	15
Number of Explosions	11	10	9	9	10	10	10

while making a total of 4 misclassifications in the test set. This might indicate a sensitivity to the assumption that the residual spectra for earthquakes taken together and explosions taken together are identical. The spectral ratio and complexity performed about equally, with the complexity measure doing slightly better on the test set. The linear detection filter (LDF) had the best overall performance record making 2 misclassifications in the learning set and only 1 misclassification in the test set. The linear matched filter was roughly comparable to the quadratic detection filter, spectral ratio and complexity, each of which had 3 to 5 misclassifications in the test set.

The above results are based on a relatively small learning set and a relatively small test set. Hence, the slight superiority of optimum filtering is not of great importance. The assumptions which guarantee that optimum filtering be optimum are only approximately satisfied. Variations are present in the individual error spectra and the use of estimated parameters may cause performance fluctuations in new data samples. However, the results are encouraging enough to speculate that optimum filtering may be as effective as the classical discriminants when applied to large data bases.

DISCUSSION

The explosion which is most earthquake-like is number 19. This event is in the region of the proposed Pechora-Kama Canal (Nordyke, 1973) where several excavation experiments have been proposed. It seems quite likely, therefore, that this event was an excavation shot. Thus no pP would have been generated, the low frequency energy would not be canceled, and the overall low-frequency appearance of the record would be explained.

Similarly, Marshall (1972) has reported that cratering experiments have been carried out near the Kazakh test site. The similarity of explosion 18 to explosion 19 suggests that it also is a cratering experiment, thus also explaining its failure to discriminate. Discrimination failures for cratering explosions are not, of course, a serious matter in the context of a test-band treaty. If these two explosions are excluded, one may say that there are no explosion discrimination failures for the 0.4-0.8 spectral ratio.

One might have expected a failure for explosion 22, reported by Marshall (1972) to have been at an announced depth of 1.53 km, and with an apparent pP-P time of 1.2 seconds. With such a large delay the 0.4-0.5 Hz energy would not be severely reduced by the spectral null at zero. However, the null at 0.8 Hz apparently eliminates enough low-frequency energy to enable the 0.4-0.8 Hz spectral discriminant to work. Thus the explosion is discriminated despite the ineffectiveness of the null at zero which is the fundamental physical phenomenon underlying the discrimination of the other events.

Another explosion was set off May 21, 1968 at Bukara (Marshall, 1972) at an announced depth of 2.45 km. Marshall obtains a delay of 1.62 seconds which would place spectral nulls at 0.62 and 1.24 Hz. We find that this event also classifies as an explosion on the 0.4-0.8 Hz spectral ratio discriminant. It

would therefore be difficult to evade this discriminant by setting off the component explosions of a shot array at considerable depth. If success were possible at some depth, one would then have to use negative discrimination on long-period (10-20 sec) P.

We must keep in mind that there is every reason to expect an occasional earthquake which will classify as an explosion on the 0.4-0.8 Hz spectral discriminant. A shallow (1-2 km), small 45° dip-slip earthquake would send out identical P-waves up and down, resulting in P-pP cancellation. These are the same events which can show compressional first motions at all teleseismic distances; and which are difficult to discriminate by M_s:m_b, Douglas et al. (1973), Blandford (1974). Another possibility is that we may find ourselves on a node of the P radiation pattern, and that this pattern will be less smoothed out by inhomogeneities at long periods than at short periods.

In a parallel study we have applied a more severe test of the idea that low frequencies are lacking in underground explosions by applying an 0.3-0.5 Hz passband filter to the events in Appendix I. Several events, including 3 of the 5 earthquakes which fail the 0.4-0.8 Hz spectral discriminant, show no detectable signal in the time domain. One can say that the minimum level is greater than that of any explosion. However, two of the earthquakes, numbers 22 and 39, still classify as explosions. The nature of these events is unknown at the present time. If we may assume that we have a fair sample of earthquakes, then at single stations we must expect a false alarm rate of 5-15% on new earthquake data. If a substantial portion of these false alarms are due to the radiation pattern problem discussed above, then their number would be substantially reduced if observations were available from a few well-distributed stations. A suitable method of analysis might be to define, in the conventional way, an m_b measured on traces filtered through a low-frequency passband, and to discriminate on the difference between this m_b and the conventional one.

Together with these results we have "0"% false alarm rate for explosions at "reasonable" and even large depths and a 100% false alarm rate for cratering explosions.

This discriminant would be extremely difficult to spoof with a shot array. Each individual shot would have less low-frequency energy than required. As we go to lower frequencies where the low-frequencies can be superposed while the shorter frequencies cancel; the amount of low-frequency energy steadily decreases. Overburying could possibly be a solution if care is taken to account for the behavior of all the spectral nulls, see the discussion above of explosion 22. It seems conceivable that a properly timed array could sufficiently cancel the predominant energy in the waveform while not cancelling the low-frequency energy, but the design analysis would have to be much more subtle than in the corresponding M_s:m_b case, and long-period (10-20 sec) P of possibly detectable for an earthquake or comparable size would still remain as a worry to the evader from the point of view of negative discrimination.

Future research should concentrate on the details of measurement of the low frequency P-wave, long-period P discrimination and thresholds, applicability of the low-frequency P discriminant as a function of distance, compilation of an extensive data base of earthquakes to "regionalize" the discriminant, and investigation of the depth and fault-plane solutions for those earthquakes which classify as explosions.

ACKNOWLEDGMENTS

The substantial job of data collection and tape manipulation was accomplished by Travis Dutterer. We are grateful also to Howard Husted for supervising the data collection effort and for running and modifying the computer programs written for the study.

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APPENDIX I

Basic Data Traces with Misclassified Events
in the Full Population Discriminants Noted as:

(1) Misclassified by linear detection filter (LDF)
(2) Misclassified by linear matched filter (LMF)
(3) Misclassified by quadratic detection filter (QDF)
(4) Misclassified by spectral ratio (Int. .4-.8 Hz)
(5) Misclassified by complexity
(6) Misclassified by complexity vs low frequency spectrum

Seismogram numbers are given beneath the event numbers. Numbers in parentheses after certain event numbers are for reference to earlier studies using these events. The source for event parameters are given with each data trace. All events near 50°N, 78°E are presumed explosions. The other presumed explosions have been identified as such by Nordyke (1973) or Marshall (1972) citing USAEC or SIPRI sources. The order of event parameters is date, latitude, longitude, m_b, and depth.

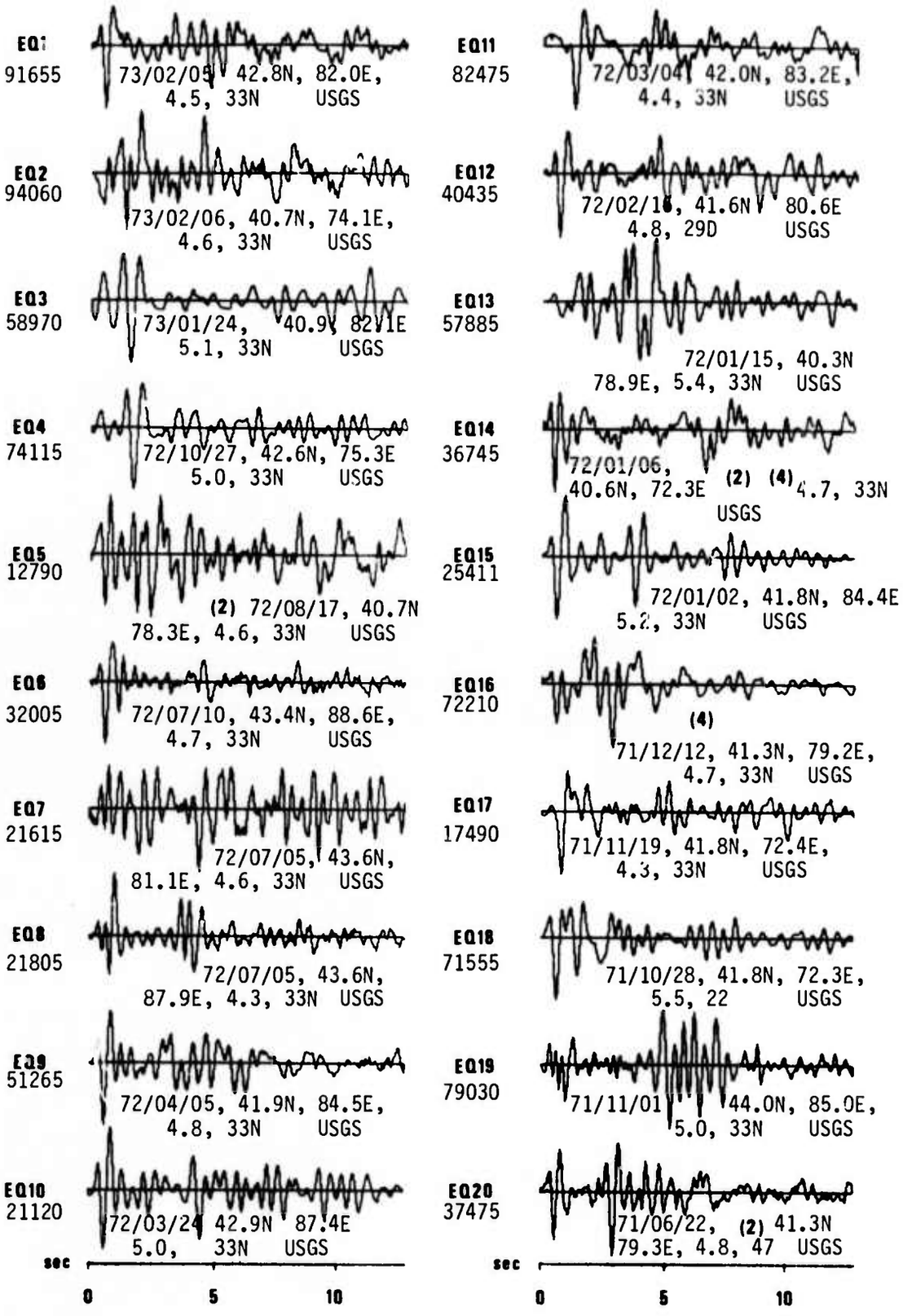

Figure A1. Earthquake Population. Page 1 of 2.

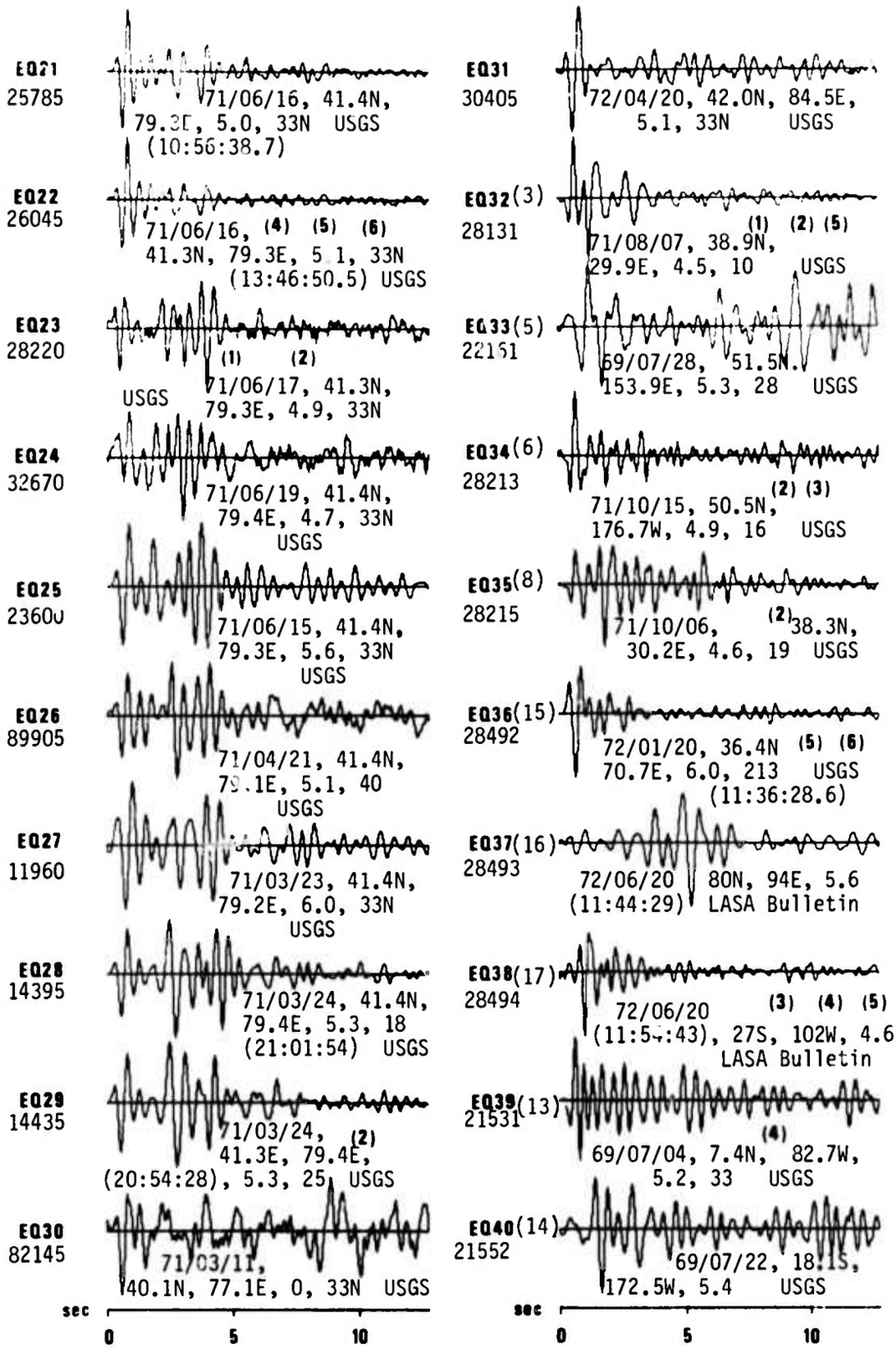

Figure A1. Earthquake Population. Page 2 of 2.

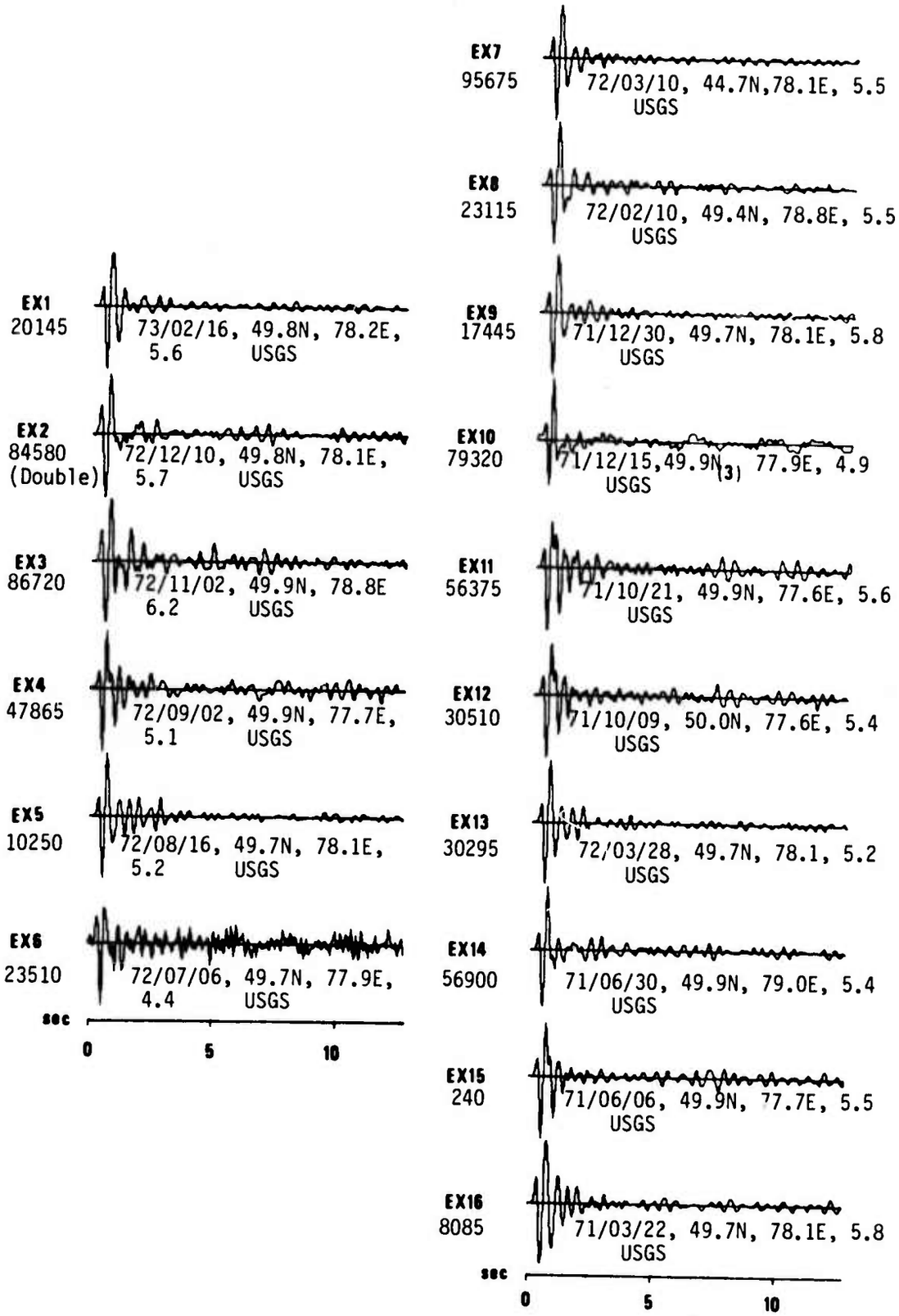

Figure A2. Explosion Population. Page 1 of 2.

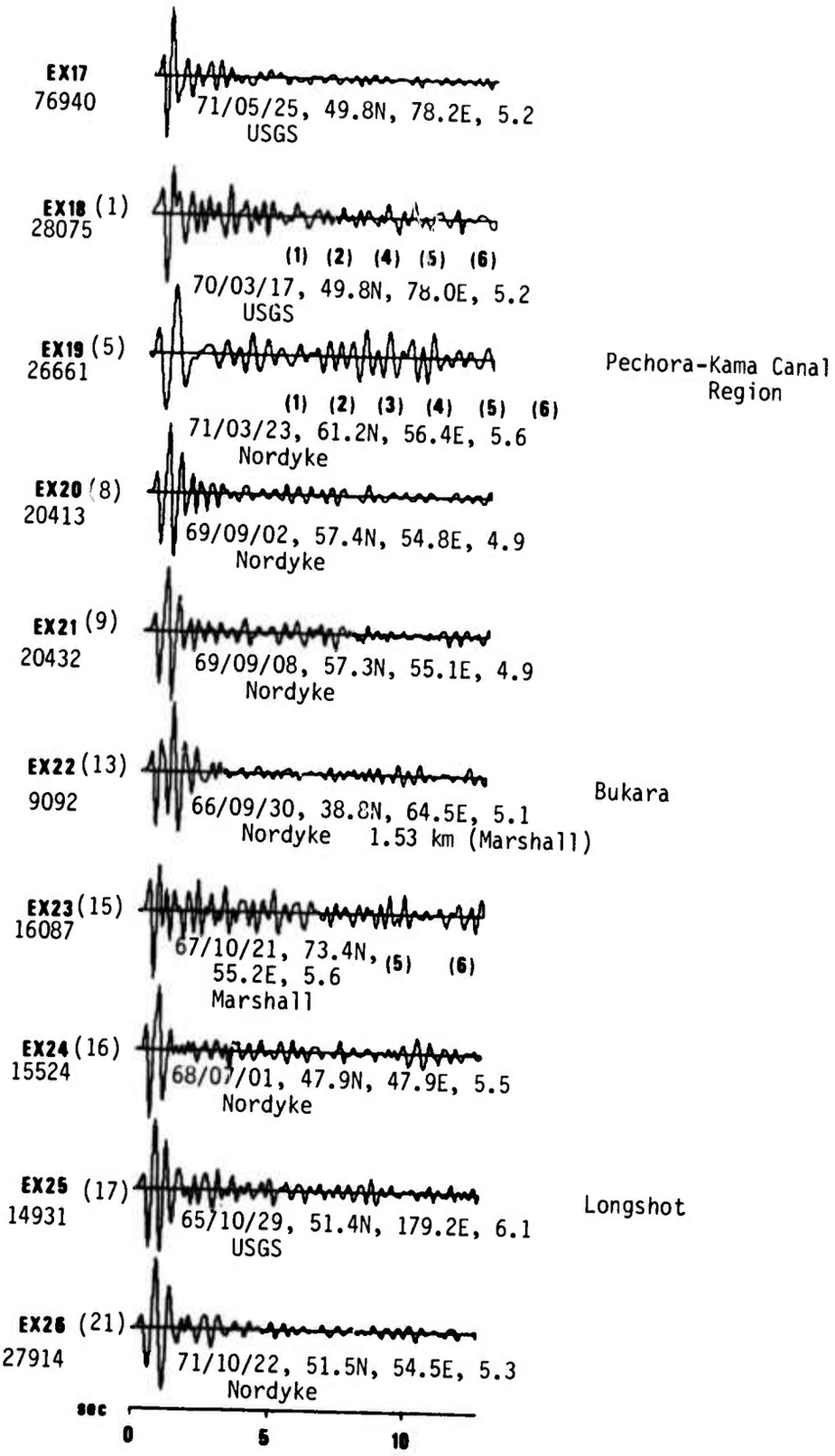

Figure A2. Explosion Population. Page 2 of 2.

APPENDIX II

Writeups of Relevent Computer Programs

A. IDENTIFICATION

1. Title: SPECES
2. Focus Identification:
3. Category:
4. Entry Points: SPECES
5. Software Systems: Fortran IV
6. Computer Configuration: IBM S/360
7. Programmer: Robert Shumway
8. Contributing Organization: Geotech
9. Program Materials Available: Source Deck, Listing
10. Date: May 1974

B. PURPOSE

Estimates the mean signal waveform and noise spectrum for each of a number of groups of time series. Each series is adjusted to unit maximum peak to peak amplitude and zero mean. Estimates for the integrated spectra of each trace in two bands (f_1, f_2) and (f_3, f_4) are computed. An estimate for the noise spectrum of each group is calculated by subtracting the mean signal for that group from each trace and averaging the spectra of the residuals.

C. USAGE

1. This is a Fortran IV main program which calls the subroutines DOT, ADD, CR, FFT, PLOP, RC, MINMAX, SPLOT, REMAV, CUM, RAVG, in the deck and ERASE, CLOCK

2. Parameters

	Col.	Parameter	Description
Card 1 (A1)	1	*	Plot character
Card 2 (10I5)	1-5	NPT	No. of pts. in each extended (2^N) series
	6-10	II	No. of groups
	11-15	NDATA	No. of pts. in series as read
	16-20	ISM	No. of pts. over which spectrum is smoothed
Card 3 (4F10.2)	1-10	SR	Sampling rate in pts/sec.
	11-20	R	Gain adjusted to amplitude R
Card 4 (4F10.2)	1-10	FR1	First frequency interval
	11-20	FR2	Cumulated is (FR1, FR2) Hz
	21-30	FR3	Second frequency interval
	31-40	FR4	Cumulated is (FR3, FR4) Hz

	Col.	Parameter	Description
Card 5 10I5	1-5 6-10	N(1)	Number of time series in group I is N(I)
	.	.	
	.	.	
	.	.	
		N(II)	
Card 6 (Etc) (I5)	1-5	NSKP	One less than desired start point for each series
.	.	.	.
.	.	.	.
.	.	.	.

3. Space Required: 72K
4. Alarms: None
5. Error Returns: None
6. Tape Mountings: Input, SYS005, Plot, SYS004
7. Formats: See parameters
8. External Symbols and Subroutines:
9. Selective Jump and Stop Settings: None
10. Timing: 13 min.
11. Cautions: None
12. References: SDAC Report, An Examination of Some New and Classical Short Period Discriminants.

A. IDENTIFICATION

1. Title: LINDIJ
2. Focus Identification:
3. Category:
4. Entry Points: LINDI1
5. Software Systems: Fortran IV
6. Computer Configuration: IBM S/360
7. Programmer: Robert Shumway
8. Contributing Organization: Geotech
9. Program Materials Available: Source Deck, Listing
10. Date: May 1974

B. PURPOSE

Searches the two group admissible linear filters for the one that maximizes the detection probability as a function of several input false alarm rates. The mean signals and noise spectra P_1 and P_2 for each of two groups (say, from SPECES) are required as input. The means and variances and threshold values for the linear detection and linear matched filters are computed. The detection probabilities are plotted as a function of the weight parameters applied to the two group spectra. Two weighting schemes $P_1-\theta P_2$ and $P_2-\theta P_1$ are considered as a function of θ.

C. USAGE

1. This is a Fortran IV main program which calls the subroutines CR, FFT, PLOP, RC, MAD, MINMAX, PROBF, QUANTF, SPLOT in the program as well as CLOCK, ERASE, SQRT, LOG, PLOT.

2. Parameters

	Col.	Parameters	Description
Card 1 (A1)	1	*	Plot Character
Card 2 (10I5)	1-5	NPT	No. of pts. (2^N)
	6-10	NIT	No. of iterations
	11-15	MIT	Method of iteration, if 1 over the admissible thetas, if 2 over thetas read in
	16-20	NALP	No. of false alarm rates considered

	Col.	Parameter	Description
Card 3 (6F10.2)	1-10	RANGE	Range of theta searched if MIT is 1
Card 4 (6F10.2)	1-10	THE(1) : THE(NIT)	THE(I) is the Ith value of theta if MIT is 2. If MIT is 1, leave those cards out.
Card 5 (4F20.5)	1-20	ALPHA(1) : ALPHA(NALP)	False alarm rate I is ALPHA(I)
Card 6 (Etc) (8F10.3)	1-80	F1(1) : F1(NPT)	Mean Signal of 1st Group
		F2(1) : F2(NPT)	Mean Signal of 2nd Group
Card 7 (Etc) (8E10.3)	1-80	F1(1) : F1(NPT)	Noise Spectrum of 1st Group
		F2(1) : F2(NPT)	Noise Spectrum of 2nd Group

3. Space Required: 58K
4. Alarms: None
5. Error Returns: None
6. Tape Mountings: Plot, SYS004
7. Formats: See parameters
8. External Symbols and Subroutines:
9. Selective Jump and Stop Settings: None
10. Timing: 30 min.
11. Cautions: None
12. References: SDAC Report, An Examination of Some New and Classical Short Period Discriminants.

A. IDENTIFICATION

1. Title: LINDI2
2. Focus Identification:
3. Category:
4. Entry Points: LINDI2
5. Software Systems: Fortran IV
6. Computer Configuration: IBM S/360
7. Programmer: Robert Shumway
8. Contributing Organization: Geotech
9. Program Materials Available: Source Deck, Listing
10. Date: May 1974

B. PURPOSE

Applies the linear matched filter and a collection of linear detection filters indexed by the spectral weighting parameter θ ($[P_1-\theta P_2]$ or $[P_2-\theta P_1]$) to a sample of time series. The new series are classified into two groups using the input critical values.

C. USAGE

1. This is a Fortran IV main program which calls the subroutines FFT, PLOP, SPLOT, MINIMAX, REMAV in the program and CLOCK, ERASE, PLOT.

2. Parameters

	Col.	Parameter	Description
Card 1 (A1)	1	*	Plot Character
Card 2 (10I5)	1-5	LF	No. of pts. in extended series (2^N)
	6-10	NTHETA	No. of values of θ to be considered
	11-15	NE	No. of time series to be classified
	16-20	NDATA	No. of data points read in
Card 3 (4F20.5)	1-20	THE(1)	Values of parameter θ
	21-40		
	:	:	
		THE(NTHETA)	
Card 4 (10I5)	1-10	ID(1)	Identification which is 1 if $P_1-\theta P_2$ is desired and 2 if $P_2-\theta P_1$ is desired
	11-20		
	:	:	
		ID(NTHETA)	

	Col.	Parameter	Description
Card 5 (8F10.3)	1-10	C(1)	Input critical values corresponding to the θ's. The last θ is a dummy value corresponding to the linear matched filter.
	11-20		
	⋮	⋮	
		C(NTHETA)	
Card 6 (Etc) (8F10.3)	1-10	XM1(1)	Mean Signal for group 1
	11-20		
	⋮	⋮	
		XM1(LF)	
		XM2(1)	Mean Signal for group 2
		⋮	
		XM2(LF)	
Card 7 (Etc) (8E10.3)	1-10	F1(1)	Noise spectrum for group 1
	11-20		
	⋮	⋮	
		F1(LF)	
		F2(1)	Noise spectrum for group 2
		⋮	
		F2(LF)	
Card 8 (Etc) (I5)	1-5	NSKP	One less than the start point for the series read in
	⋮	⋮	
	⋮	⋮	

3. Space Required: 57K
4. Alarms: None
5. Error Returns: None
6. Tape Mountings: Input, SYS005, P1[illegible] YS004
7. Formats: See parameters
8. External Symbols and Subroutines:
9. Selective Jump and Stop Settings: None
10. Timing: 15 min.
11. Cautions: None
12. References: SDL Report, An Examination of Some New and Classical Short Period Discriminants.

A. IDENTIFICATION

1. Title: QUAD1
2. Focus Identification:
3. Category:
4. Entry Points: QUAD1
5. Software Systems: Fortran IV
6. Computer Configuration: IBM S/360
7. Programmer: Robert Shumway
8. Contributing Organization: Geotech
9. Program Materials Available: Source Deck, Listing
10. Date: May 1974

B. PURPOSE

Computes a number of non-linear discriminants for a collection of time series including (1) Quadratic detection filter output, (2) Spectra accumulated over the bands (f_1, f_2) and (f_3, f_4), (3) Complexity, (4) Skewness (third moment), (5) kurtosis (fourth moment).

C. USAGE

1. This is a Fortran IV main program which calls the subroutines CR, FFT, PLOP, RC, ADD, SPLOT, MINMAX, REMAV, DOT, CUM, DIST, RAVG, SK.

2. Parameters

	Col.	Parameter	Description
Card 1 (A1)	1	*	Plot Character
Card 2 (8F10.3)	1-10	EP	Small value to add to each noise spectrum
	11-20	FR1	Low frequency integrated
	21-30	FR2	Spectrum (FR1, FR2)
	31-40	FR3	High frequency integrated
	41-50	FR4	Spectrum (FR3, FR4)
Card 3 (10I5)	1-5	LF	Length of extended data series (2^N)
	6-10	NDATA	No. of data pts. read in
	11-15	NE	Number of time series
	16-20	IST	Complexity is computed starting at pt. IST + 1.

	Col.	Parameter	Description
Card 4 (Etc) (8F10.3)	1-10	XM1(1) : XM1(LF)	Mean signal for 1st type of event
		XM2(1) : XM2(LF)	Mean signal for 2nd type of event
Card 5 (Etc) (8E10.3)	1-10	F1(1) : F1(LF)	Noise spectrum for 1st type of event
		F2(1) : F2(LF)	Noise spectrum for 2nd type of event
Card 6 (Etc) (I5)	1-5	NSKP :	One less than the start point for each series read in

3. Space Required: 64K
4. Alarms: None
5. Error Returns: None
6. Tape Mountings: Input, SYS005, Plot, SYS004
7. Formats: See parameters
8. External Symbols and Subroutines:
9. Selective Jump and Stop Settings: None
10. Timing: 23 min.
11. Cautions: None
12. References: SDAC Report, An Examination of Some New and Classical Short Period Discriminants.